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The Weight of the World Is Quantum Chromodynamics

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Ab initio calculations of the proton and neutron masses have now been achieved, a milestone in a 30-year effort of theoretical and computational physics.

The reason for excitement surrounding the start-up of the Large Hadron Collider (LHC) in Geneva, Switzerland, has often been conveyed to the general public as the quest for the origin of mass—which is true but incomplete. Almost all of the mass (or weight) of the world we live in comes from atomic nuclei, which are composed of neutrons and protons (collectively called “nucleons”). Nucleons, in turn, are composed of particles called quarks and gluons, and physicists have long believed that the nucleon’s mass comes from the complicated way in which gluons bind the quarks to each other, according to the laws of quantum chromodynamics (QCD). A challenge since the introduction of QCD (*1*–*3*) has been to carry out an *ab initio* calculation of the nucleon’s mass. On page 1224 of this issue of *Science*, Dürr *et al.* (*4*) report the first such calculation that incorporates all of the needed physics, controls the numerical approximations, and presents a thorough error budget. Because these accurate calculations agree with laboratory measurements, we now know, rather than just believe, that the source of mass of everyday matter is QCD.

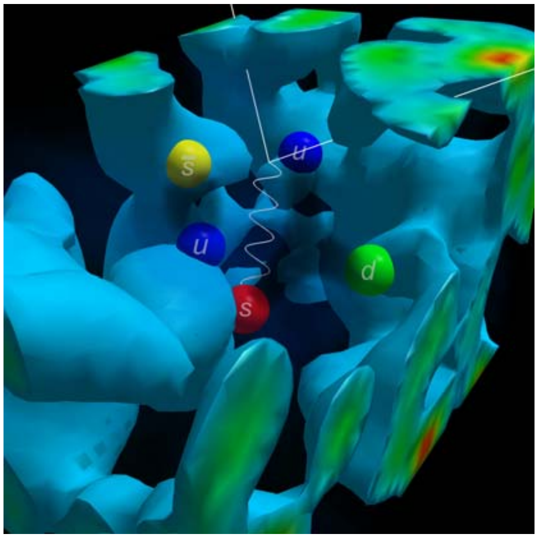
The key tool enabling this advance is lattice gauge theory (*5*), a formulation of QCD and similar quantum field theories that replaces space-time with a four-dimensional lattice. To picture the lattice, think of a crystal with cubic symmetry evolving in discrete time-steps. Lattice gauge theory has theoretical and computational advantages. The watershed theoretical result of QCD is the weakening at short distances of the coupling between quarks and gluons, called asymptotic freedom (*2*, *3*). The flip side is the strengthening of the coupling at large distances, which is responsible for confining quarks and gluons inside one of the broad class of particles called hadrons.

Confinement emerges naturally in lattice gauge theory at strong coupling (*5*). The lattice also reduces everything we would want to calculate to integrals that, in principal, can be evaluated numerically on a computer. Thus, 30 years ago a challenge was set: Use numerical computations to connect strongly coupled lattice gauge theory with weakly coupled asymptotic freedom, thereby recovering the hadron masses of our world, with continuous space and time.

The first numerical efforts (*6*) showed this approach to be sound, but as the subject developed, two major obstacles arose, both connected to physics and to computation. The first obstacle is describing the “vacuum.” In classical physics, the vacuum has nothing in it (by definition), but in quantum field theories, such as QCD, the vacuum contains “virtual particles” that flit in and out of existence. In particular, the QCD vacuum is a jumble of gluons and quark-antiquark pairs, so to compute accurately in lattice QCD, many snapshots of the vacuum are needed.

The second obstacle is the extremely high amount of computation needed to incorporate the influence of the quark-antiquark pairs on the gluon vacuum. The obstacle heightens for small quark masses, and the masses of the up and down quarks are very small. An illustration of the vacuum and the quark-antiquark pairs is shown in the figure. The fluid material is a scientifically accurate snapshot, sometimes called the QCD lava lamp, of a typical gluon field drawn from a lattice-QCD computation (*7*). Three of the quarks (up + up + down, or *uud* for short) could constitute the proton, but a strange quark (s) and strange antiquark ($\bar{s}$) have popped out of the vacuum: The proton has fluctuated into a Λ hyperon (uds) and a kaon $(\bar{s}u)$.

To make progress despite limited computing power, 20 years’ worth of lattice QCD calculations were carried out omitting the extra quark-antiquark pairs. The computation of the nucleon's mass passed some technical milestones (*8, 9*) but was still unsatisfactory. As well as demonstrating the validity of strongly coupled QCD, we want to compute properties of hadrons *ab initio*, to help interpret experiments in particle and in nuclear physics. Without the quark-antiquark pairs, it is impossible to quantify the associated uncertainty.



The busy world of the QCD vacuum. The interior of a hadron, such as the proton or neutron, is not static. Gluons fluctuate in a collective fashion, illustrated by the red-orange-yellow-green-blue fluid. Sometimes the gluon field produces extra quark-antiquark pairs; here, a proton (*uud*) has fluctuated into a Λ hyperon (*uds*) and a kaon $(\bar{s}u)$. Animations of these phenomena are available at (*7*). **CREDIT:** Derek Leinweber, CSSM, University of Adelaide

A breakthrough came 5 years ago, with the first wide-ranging calculations incorporating the back-reaction of up, down, and strange quark pairs (*10*, *11*). This work used a mathematical representation of quarks that is relatively fast to implement computationally (*12*), and these methods enjoyed several noteworthy successes, such as predicting some then-unmeasured hadron properties (*13*). This formulation is, however, not well suited to the nucleon, and so a principal task for lattice QCD remained unfinished.

Dürr *et al.* use a more transparent formulation of quarks that is well suited to the nucleon and other baryons (hadrons composed of three quarks). They compute the masses of eight baryons and four mesons (hadrons composed of one quark and one antiquark). Three of these masses are used to fix the three free parameters of QCD. The other nine agree extremely well with measured values, in most cases with total uncertainty below 4%.

For example, the nucleon mass is computed to be 936 ± 25 ± 22 MeV/c^2 compared with 939 MeV/c^2 for the neutron, where c is the speed of light and the reported errors are the statistical and systematic uncertainties, respectively. The final result comes after careful extrapolation to zero lattice spacing and to quark masses as small as those of up and down (the two lightest quarks, with masses below 6 MeV/c^2). The latter extrapolation may not be needed in the future. Last July, a Japanese collaboration announced a set of lattice-QCD calculations (*14*) of the nucleon and other hadron masses with quark masses as small as those of up and down.

These developments are serendipitously connected to the work honored by this year's Nobel Prize in physics. The lightest hadron—the pion—has a mass much smaller than the others. Before QCD, Nambu (*15*) proposed that this feature could be understood as a consequence of the spontaneous breaking of chiral symmetry (*16*). In QCD, it has been believed, the spontaneous breaking of this symmetry by the vacuum predominates over an explicit breaking that is small, because the up and down quarks' masses are so small. Lattice QCD (*4*, *10*, *11*, *13*, *14*) simulates and, we see now, validates these dynamical ideas in the computer. Moreover, this success puts us in a position to aid and abet the understanding of the role of quark flavor (*17*), including asymmetries in the laws of matter and antimatter (*18*), for which Kobayashi and Maskawa received their share of the Nobel Prize.

Dürr *et al.* start with QCD's defining equations and present a persuasive, complete, and direct demonstration that QCD generates the mass of the nucleon and of several other hadrons. These calculations teach us that even if the quark masses vanished, the nucleon mass would not change much, a phenomenon sometimes called "mass without mass" (*19*, *20*). It then raises the question of the origin of the tiny up and down quark masses. The way nature generates these masses, and the even tinier electron mass, is the subject of the LHC, where physicists will explore whether the responsible mechanism is the Higgs boson, or something more spectacular.

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